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Floods with Debris and Anthropogenic Waste: Accounted for or Not?

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Abstract

Natural floods are unusual extreme events resulting from significant or prolonged rainfall, which sometimes turn into disasters. Trends indicate that these phenomena may become more frequent in the future. Therefore, many solutions are being implemented in practice to deal with the problem. In the European Union, enhanced measures have been taken, including the assessment and mapping of flood risks, triggered by the adopted legislation. Despite these solutions, flood disasters continue to occur, even in areas included in Flood Risk Management Plans but outside the territories designated as vulnerable. To investigate the reason, a study was conducted accounting for flood genesis and the role of flood debris and anthropogenic waste as a factor that can worsen the harmful impact of these events. It was considered whether there is a gap in the application of current methods and legislation. A brief review was performed concerning the physical description of the phenomenon and the evaluation methods used, accounting for the role that debris and anthropogenic waste play in them. Some main practices and applicable tools were also discussed in brief. As an illustration of the impact, a case study of a recent significant flood in Bulgaria was also presented. This flood affected an area that is not identified as at risk under the Flood Risk Management Plans developed in accordance with the European and Bulgarian legislation and requirements. The information presented here confirms the significant role that debris and anthropogenic waste play in the process of turning a flood into a disaster and highlights the need for additional work concerning their proper incorporation in both the regulation and assessment processes.

Keywords: flood; extreme flood formation; flood debris; FRMPs; flood vulnerability; extreme events; flood risk mapping

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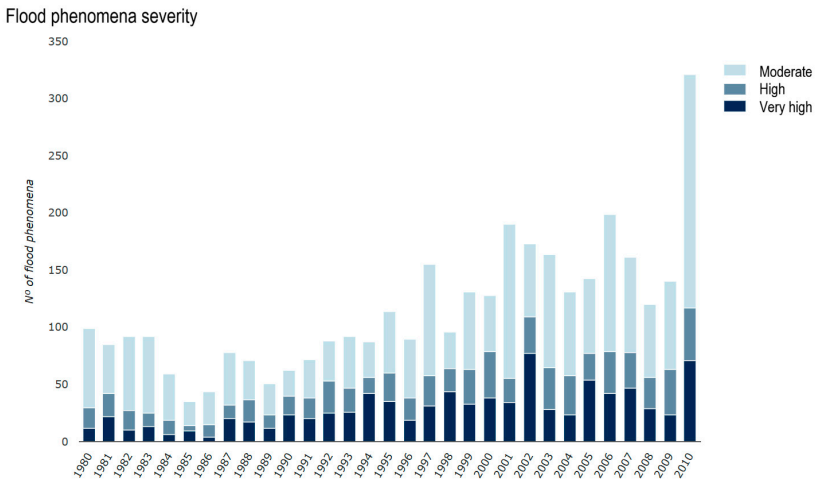
1. Introduction

Floods are extreme events that occur in nature after significant and/or long-lasting precipitation, resulting in hazards or disasters in many cases due to local conditions. According to the World Meteorological Organization (WMO) [1], for the period 1970–2019, 50% of all recorded disasters (including technological hazards), as well as 45% of associated deaths and 74% of economic losses, were attributable to weather, climate, and water-related factors. Data show that the number of disasters has increased fivefold over the past 50 years; while 711 disasters were recorded during the 1970–1979 period, this figure rose to 3536 during 2000–2009. Water-related hazards predominate globally in terms of both human casualties and economic losses. Globally, 44% of disasters have been linked to floods (riverine floods—24%; general flooding—14%). In Europe, the 1672 disasters recorded between 1970 and 2019 resulted in a total of 159,438 deaths and economic losses amounting

to 476.5 billion US dollars; the greatest economic losses are caused by floods (38%) and storms (32%). These events have been investigated in numerous studies, confirming the data presented above. Additional initiatives taking place at the international, EU, or local level involve various methods to improve our understanding of the direct and indirect socio-economic consequences of climate change, with floods considered an integral part of the associated impacts. They also confirm the problem [2–4]. Distinct signs indicate that negative flood phenomena will persist and intensify in the future [5–9]. Projections under both high- and medium-emissions scenarios show high confidence in extreme precipitation increase, in the northern, central, and eastern European regions and in the Alpine area; for southern Europe, they are more mixed [10]. As a result, the expected heavy rainfall would raise water levels, leading to extreme flooding. Investigations show that as a result of such occurrences, at the end of the century, the number of people exposed to annual river flooding in Europe is projected to be 252,000 under the 1.5 °C global warming scenario; 338,000 under the 2 °C scenario; and 484,000 under the 3 °C scenario—more than three times the current number [11].

Regarding IPCC, it has already been observed that climate change is altering the intensity, frequency, and location of floods [2]. The number of floods registered in Europe between 1980 and 2010 shows a persistent increasing trend (Figure 1) [12].



Note: Flood severity is an assessment of flood phenomena magnitude. It considers the reported values on frequency, reported total damage (in euros and descriptive classes), number of flood events within one flood phenomenon unit and severity classes as reported in the Dartmouth Flood Observatory database. e.g. all phenomena with fatalities are in the severity class 'very high'.
Source: EEA, 2016; European past floods provided by the EEA. Dataset contains information on past floods in Europe since 1980, based on the reporting of EU Member States for the EU Floods Directive (2007/60/EC) and combined with information provided by relevant national authorities and global databases on natural hazards.

Figure 1. Reported flood phenomena between 1980 and 2010, EEA [12].

However, exposure to flood risk is not only determined by climatological factors. General features are also important, such as the area's vulnerability to flooding, specific local geographical and topological conditions, land coverage, anthropogenic interventions, and their physical state related to the increase in water level, the increasing degree of soil sealing, the formation and transportation of debris and flood waste, etc. In practice, these factors predispose to flood formation and development and the associated consequences, and in many cases they are underestimated. A typical example is the generation and downstream transportation of debris and flood waste, which, depending on the specific local conditions, can predetermine and intensify flood impacts.

To prevent and mitigate all flood obstacles, various measures are adopted in practice—legislative, administrative, and local. In support of this, new knowledge and practically applied approaches are actively being developed and used [13–19]. However, even after all of these measures have been taken, damaging floods are still being frequently observed.

This raises the question of whether these measures are sufficient and whether something is being missed. To address this question, this article focuses on the physical aspects of floods and their connection with the adopted legislation in the EU, as well as on the assessment of flood flow and the incorporated debris and anthropogenic waste. To illustrate the strengths and weaknesses of the process, a specific example of a recent flood in Bulgaria is briefly presented.

2. Legal Requirements in the EU

The frequent occurrences of climate extremes and floods inevitably exert a strong impact on nature, society, and human activities. To prevent and mitigate all flood obstacles, various measures are adopted in practice—legislative, administrative, and local. Regarding water, the EU has adopted various directives, strategies, regulations, and supporting documents outlining the main lines of action. Each member state is encouraged and assisted in their implementation with regard to particular local specificities. This is why the specified frameworks are quite wide and comprehensive. In the EU, the Water Framework Directive (WFD) [20] is a primary piece of legislation for water protection and sustainable water body management. In it, floods are considered "extreme events" rather than standard features of aquatic ecosystems. As traditional flood management structures often deal with serious environmental damage, the WFD requires that flood protection measures be coordinated with the ecology of the river basin. This is taken into account in the development of supporting River Basin Management Plans (RBMPs) [20–23], where floods are addressed through coordinated planning with Flood Risk Management Plans (FRMPs) [22,23], the main supporting instruments for the implementation of the EU Floods Directive [22]—the most comprehensive approach to the problem. It defines flooding as a "temporary covering of land by water that is not normally covered by water". It presents floods not as isolated disasters but as natural river dynamics that require coordinated assessment, mapping, and risk management across the member states. All member states must follow a cyclical, three-step process to map and evaluate how floods affect their territory:

- Preliminary Flood Risk Assessment (PFRA): Countries first review their territories to identify Areas of Potential Significant Flood Risk (APSFRs).
- Flood Hazard Mapping: For identified risk areas, authorities map the geographical extent of floods and indicate water depths, levels, and flow velocities.
- Flood Risk Maps: These maps detail the potential consequences of the hazard scenarios, showing estimated numbers of affected inhabitants and the types of economic activities at risk.

This is performed in 6-yearly cycles, aiming at reducing the risk of flood damage in the EU. Each period is accompanied by a relevant Flood Risk Management Plan (FRMP) [22,23] that is periodically upgraded. The first one covered the period 2010–2015, the second one concerned 2016–2021, and the third stage is currently being implemented, covering the period 2022–2027. Each plan builds on the previous one, with more detailed elements. At the same time, the identification of new key circumstances may prompt a revision of the achieved tasks.

To obtain more sustainable results, developments in this direction are synchronized with other existing legislation, including the Marine Directive [24] and the Habitats Directive [25]. For comparison, in the United Kingdom, the primary statute concerning floods is the Flood and Water Management Act 2010 [26], connected to the Flood and Coastal Erosion Risk Management and the duties regarding risk assessment and sustainable drainage. In the United States, flooding is addressed in the Flood Protection Act of 1973 [27], which designates Flood Protection Areas (FDPAs)—Special Flood Hazard Areas (SFHAs) with a high risk of flooding (at least a 1% annual chance of flooding).

The presented legislative norms stimulate new solutions and developments in the field, which are carried out in the individual countries but also through broad international cooperation, which leads to even better results. Widely used approaches are geospatial assessments, for the determination of flood runoff and connected inundated areas on a large scale in flood risk assessments and flood risk area mapping; hydraulics approaches, which are widely used for the determination of flood wave properties in open flows and their propagation on the local scale; and hydrological assessments, for the determination of the chance of flooding, etc. These approaches involve some simplification but give good results. However, significant flooding occurs even outside the areas defined by the measures presented above. This may be related to a gap in terms of under-rated elements. Given the specifics of the genesis of floods and the dangerous role that debris and flood waste can play, an analysis was initiated to see if this was not precisely an underestimated element. For this purpose, the participation of debris and anthropogenic waste in the estimated procedures is carefully observed. As a case study, a recent flood in Bulgaria is also briefly presented.

3. Flood Genesis, Debris, and Anthropogenic Waste: Assessments Used

When it rains, water that reaches the ground begins moving towards lower-lying areas, collecting in streams and rivers. In the case of heavy or prolonged rainfall, this flow can exceed the capacity of the riverbed, flooding the surrounding areas. The physical propagation of this flow is in the form of a flood wave. This wave is formed by the water masses coming from the territories located above, in addition to the usual base flow (Figure 2) [28].

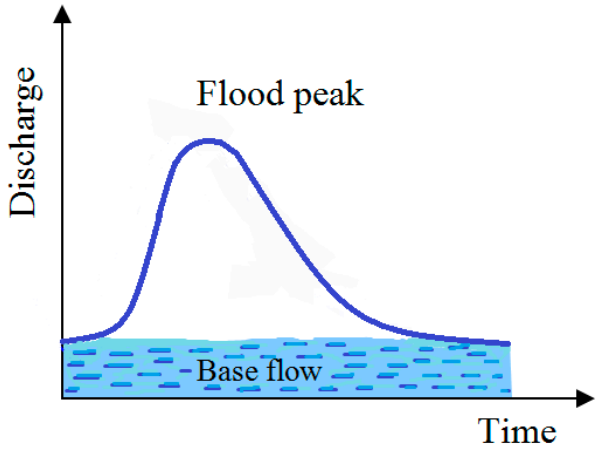


Figure 2. Propagation of the flood wave.

The flood peak (the absolute maximum flow volume) is formed after some period of intense precipitation, following the precipitation rate. It is a combination of the rapid surface runoff and the delayed arrival of groundwater converging into single drainage areas. In the case of actual floods, the situation is more complex: floodwaters interact with the surrounding environment, mixing with debris and anthropogenic waste. This is closely connected to heavy rainfall or storm impacts and the formation of harmful flows that affect the surrounding environment and damage and uproot existing vegetation (grasses, shrubs, and trees), stripping away the fertile topsoil, destroying agricultural crops, triggering landslides and the displacement of soil and rock masses, and damaging or destroying riverbanks and beds, bridges, levees, infrastructure, and related facilities (Figure 3).

Figure 3. Examples of storm and flood consequences. (**a**) Tree destruction as a result of intense rainfall; (**b**) flood in an urban area; (**c**) bridge destruction after a flood; (**d**) road infrastructure destruction after a flood; (**e**) washing away of a bridge by a flood: (**e1**) during and (**e2**) after the flood.

Such interactions fundamentally alter the flow's structure and behavior in various directions, including the type of motion, the nature and magnitude of the acting forces, and all associated parameters. While they are closely linked to location specifics, a suitable framework of potential elements can facilitate the assessment process. Existing classifications are directly linked to various assessments regarding flood-related debris and anthropogenic waste elements that are formed during these phenomena. These are used to assess and quantify the volume, quantity, composition, and type of debris, as well as evaluate options for temporary debris management sites and temporary disaster waste management sites; to identify health hazards, environmental hazards, and environmental impacts; to consider the economic costs and economic benefits; and to account for community priorities, social capital, and psychological effects; to decide on funding, regulations, policy, planning, and the circular economy [29–31]. Developed for temporary debris management, here follows a detailed classification of disaster debris and waste elements [30,31], including:

- Vegetative debris or green wastes;
- Sediment/soil and rock;
- Household hazardous waste (refrigerant, oils, pesticides, etc.);
- Construction and demolition debris from damaged buildings and infrastructure (such as roads, pipe networks and other services);
- Industrial and toxic chemicals (including fuel products);
- Putrescible wastes (rotting food, etc.);
- Vehicles and vessels;
- Recyclables (plastics, metals, etc.);
- Electronic and white goods;
- Waste from disaster-disturbed pre-disaster disposal sites;

- Human and animal corpses;
- Excessive unwanted donations;
- Healthcare wastes;
- Rotten food from power outages;
- Emergency relief food packaging.

The presented classification is quite comprehensive, showing the elements that play a significant role in flood flows. To obtain a good assessment, the presented elements should be incorporated into the calculation procedures, taking into account the specific characteristics of the object under study.

3.1. Evaluation Methods and Tools

Fluid dynamics is closely linked to the study of fluidic motion. Such a process is complex, developing in time and space. It can be described by the fundamental principles of conservation of mass, Newton's second law, and conservation of energy [32–36]. It has a three-dimensional pattern that can be described well by the Navier–Stokes equations.

The Navier–Stokes Equation (1) describes flow transportation by applying Newton's second law to continuous fluids [33–35]:

$$\begin{aligned} \rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right) &= -\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+\rho g_x \\ \rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right) &= -\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+\rho g_y \\ \rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right) &- \frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho g_z \end{aligned} \tag{1}$$

where u, v, and w represent the velocity components in regard to the coordinates x, y, z and time t; p is the pressure, ρ represents the density, μ represents the shear viscosity, and g is the acceleration due to gravity.

They mathematically track how fluid masses are transported over time, balancing internal forces (pressure and viscous friction) with external forces (gravity). They establish how flow variables like velocity and pressure change over space and time. Their application is connected to the continuity Equation (conservation of mass) (2), ensuring that the net rate of fluid entering a region is equal to the rate leaving it, when ρ is constant:

$$\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}+\frac{\partial u_z}{\partial z}=0 \tag{2}$$

The three-dimensional Navier–Stokes equations are too complex; thus, for large-scale flows, they are simplified to the more easily applicable form of the Saint-Venant equations—a set of two non-linear partial differential equations that model unsteady, one-dimensional open-channel flow under the assumption that horizontal dimensions significantly exceed the vertical depth. They describe how water depth and velocity change over time, and the propagation of flood waves in rivers, canals, urban drainage networks, etc. [32–35]. The set includes the following:

(1) Continuity equation (conservation of mass) in the form (3):

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \tag{3}$$

(2) Momentum equation (conservation of momentum):

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+gA\left(\frac{\partial z}{\partial x}+S_f\right)=0 \tag{4}$$

where A is the cross-sectional area, Q is the flow discharge, v is the mean flow velocity that varies with space (x) and time (t), represented by its defining features, S_f is the friction slope, and z is the elevation of surface above a datum at the section.

The presented theoretical framework is widely used. However, it must be emphasized that it is developed for Newtonian fluids (with constant viscosity). When debris (sediment, soil, rocks, etc.) are suspended in water, they change the flow rheology. For example, high sediment and debris concentrations alter the overall fluid density (Figure 4) [37].

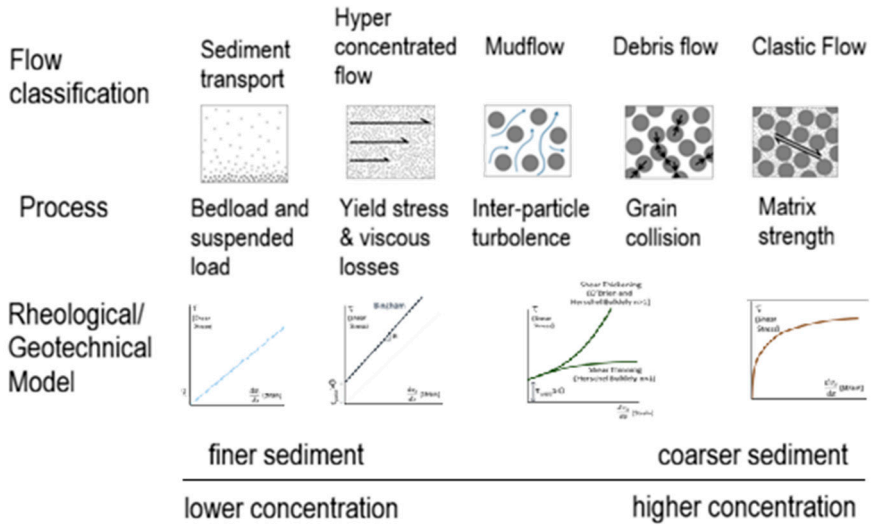


Figure 4. Flow cases, based on HEC-HMS interface courtesy of the U.S. Army Corps of Engineers, Hydrologic Engineering Center, HEC-RAS Mud and Debris Flow [37].

In the case of floods, the turbulent movement forces the nonhomogeneous distribution of solids within the liquid. The flow behaves as a non-Newtonian fluid. At rest, solid particles act as Bingham fluids (as a solid) but flow like a fluid once a minimum stress is applied. Depending on particle composition, a fluid's viscosity can either decrease (shear thinning) or increase (shear thickening) when a shearing force is applied, and as these fluids have internal strength, they can "run out" and come to a complete stop even on steep slopes, whereas standard Newtonian water would continue to flow. In such cases, standard formulas cannot be directly applied. For real floods, investigations must be adapted to account for the rheology of the particular debris [38]. Specialized programs for fluid mechanics investigations are Ansys® Fluent, Release 2024 R1, ANSYS, Inc. (Canonsburg, PA, USA), FLOW-3D Version 2026R1 [Computer software]. (2026). Santa Fe, NM, USA: Flow Science, Inc., etc., which allow some theoretical investigations. It must also be noted that, in many cases, real-world applications are not tested [39]. Due to the turbulence of the flow, real flood data are not reproducible.

In the case of large-scale debris and/or anthropogenic waste, the processes become even more complex. The geometry of the flow system is not stabile. For example, the composition of woody debris carried by creeks and rivers during floods is variable. It can range from short logs, with a diameter of few centimeters, to the size of whole trees, dropped or eradicated by wind during storms, several meters in length and up to 1 or 2 m in diameter, also considering the size of canopy and roots [40]. Trees with huge roots can "dredge" the bottom and therefore move very slowly and bend their tracks [41], while light buoyant logs can follow the main current (also depending on the presence of river bends and meanders). Nevertheless, research in this area is being conducted within the field of fluid mechanics. During such studies, simplified hypotheses are applied, namely, that the current is straight, and hence the motion is uniform in space and the debris follows the channel track; a simplified approach for very wide channels covered by a homogeneous

solid carpet of floating debris is also used. These studies confirm the need for and the possibilities of reformulating the equations used [42–46].

To obtain a better impression of the methods used for debris evaluation in practice, here follows a brief presentation of these methods:

1. Volume balance approach, using volume balance methods to predict the flooded area (A) as a function of total volume (V):

$$A = kV^d, \tag{5}$$

where k and d are empirical coefficients.

To give an idea of their application, it can be mentioned that when the volume of debris flow is estimated by measuring the area and average thickness of deposited material in situ, the errors associated with these estimates can be assumed to be 50–60% [44]. The mentioned studies are highly specific and do not find large-scale application in practice.

2. Limiting topographic methods, related to the fan slope Sd or to parameters related to the energy dissipated along the depositional path. Vandre [45] proposed an empirical approach to estimate the runout distance of a debris flow:

$$R = \omega \Delta H, \tag{6}$$

where R is the runout distance, ΔH is the elevation difference between the initiation point and the point where deposition starts, and ω is an empirical constant. According to Vandre's data [45], the value of ω is 0.4 (i.e., the runout distance is 40% of the elevation difference ΔH). The rules applied to govern debris flow transport and sediment deposition are as follows:

- For slopes greater than 10°, the debris flow continues unconditionally;
- For slopes between 4° and 10°, the debris flow comes to a halt either when the condition expressed by Equation (6) is satisfied or upon reaching the 4° slope;
- For slopes less than 4°, the debris flow halts unconditionally and deposits all remaining material.

3. Empirical equations: they use variables such as debris flow volume (V), potential mass energy (H), fan slope (Sd), upstream gradient (θu), mean slope angle of the whole path (β), and catchment area (AC) to predict the runout distance on the fan and the total distance traveled.
4. Physically oriented methods, using dynamic methods that consider mass, momentum, and energy conservation to simulate the propagation of debris flows using 1D or 2D models; numerical models that adopt a variety of hypotheses for solving the motion equations and take into account different rheological models of the material involved.

3.2. Assessment Works

Recent flood assessment methods and tools incorporate the presented basis with particular spatial data about the terrain, structures (existing, destroyed, or projected), and land use, through especially dedicated spatial integration systems. Some of them translate the real-world topography properties with hydraulic computation models; others use the Geographic Information System (GIS), overlaying high-resolution geographic and environmental data onto the landscape, using statistical, machine learning, and physical modeling techniques. Both approaches employ user interfaces, hydraulic analysis components, data storage and management, graphics, and reports for some particular investigations or the development of commercial assessment products. They integrate hydrology and hydraulic calculations. For initial information, they use topographic measurements or LiDAR data,

as well as GIS DEM. Subsequently, specific models simulate the dynamic values of flood depth and velocity and aid in the determination and mapping of flood-prone areas.

For practical purposes, many water and flood assessment tools and commercial products are developed. To account for the needs of flood flow investigations, here follows a brief presentation of the most suitable assessment tools for large-scale flood flows. They are selected with regard to the possibility of accounting for flood debris and anthropogenic waste in flows.

The Hydrologic Engineering Center (CEIWR-HEC) proposes various river analysis products (HEC-RAS). The HEC-RAS Mud and Debris Flow (Non-Newtonian) [37] considers mud and debris flows as non-Newtonian fluids rather than standard "clear water". The software computes internal losses in the momentum equation using specific rheological models, rather than standard Newtonian equations. It proposes the implementation of modified 1D Saint-Venant equations that incorporate Manning's equation (to account for channel roughness) and additional forces that can collapse the slopes; and also 2D Shallow Water equations and the 2D Diffusion Wave Equation. Estimations are provided by four non-Newtonian flow types, presented in the debris library: hyper-concentrated flow, simulated by the Bingham plastic rheological model; mudflow with turbulent–quadratic rheology; grain flow with turbulent–dispersive rheology; and debris flow with Coulomb rheology. There are also possibilities for sediment and classic flow transportation.

CEIWR-HEC also proposes Flood Damage Reduction Analysis (HEC-DRA) [47]. It provides an evaluation of alternative flood damage reduction plans using annual exceedance probabilities, risk analysis, and economic impacts, but it is not directly connected to the flood flow investigation.

The Danish Hydraulic Institute (DHI) proposes the Integrated Urban, River, and Flood Modeling Platform MIKE + [48]. It provides assistance for professionals in identifying solutions to mitigate heavy rain and surface pollutants, assess flood control measures, and implement real-time flood forecasting systems for urban and rural areas. It is an all-in-one water modeling platform that combines 1D and 2D river, coastal, and urban drainage networks. MIKE+ has largely absorbed the capabilities of MIKE FLOOD. This previous MIKE FLOOD product served for 1D, 2D, and coupled 1D–2D riverine and overland modeling [49]. The 1D model was performed as a numerical engine used to solve unsteady flows using the Saint-Venant equations for 1D unsteady flow. 2D modeling refers to a two-dimensional representation of the flow. It can use LiDAR and GIS data. The flow specifics are defined by selecting the particular properties. There is a "Bathymetry" part; soil data are presented in four groups; land use is also presented as crop, pasture, or woodland; buildings are presented as polygons; and Manning's value for roughness must be selected, as well as the viscosity. Considered issues are peak flood discharge; channel and flood plain roughness; expansion and contraction coefficients; starting water levels, tidal conditions, or control gate operations; channel configuration, including the spacing, location, and definition of cross-sections; ice-jamming and debris blockage; and sedimentation and sand bars.

Geographic Information Systems (GISs) also facilitate the determination of flood flow, accounting for debris and anthropogenic waste. For example, Innovyze InfoWorks ICM deeply integrates with the Esri's GIS environment, allowing the use of ArcGIS Desktop 10.7 as an alternative map control directly within the software. It features advanced 2D modeling tools that can ingest shapefiles to automatically build complex, unstructured 2D hydraulic meshes. For each mesh element, depths, cumulative infiltration, eddy viscosity, saturation flag, the moisture content of the upper zone, the time needed to the drain upper zone, the velocity of water, etc., are available. The danger of debris in the 2D flood simulation is assessed by calculating a standardized Flood Hazard Rating (HR). This

rating incorporates a specific Debris Factor, connected to the dominant land use (pasture, woodland, or urban zone), flood depths, and velocities. It is 0.5 for depths < 0.25 m and 1.0 for depths > 0.25 m [50]. Such values are adopted by the DEFRA Flood Hazard Technical Report, which emphasizes the need for additional investigations on the topic [51].

The information presented in this section clearly demonstrates that the behavior of debris and anthropogenic waste during floods is poorly and insufficiently assessed. The reason may lie in their complex nature, the unpredictability of their formation and transport, and the limited theoretical and mathematical knowledge for their characterization. This entails numerous simplifications that affect the quality of the results.

To illustrate the problem, an analysis of a recent major flood in Bulgaria is presented in the next section.

4. Case Study

On 3 October 2025, the meteorological situation on the Bulgarian Black Sea coast was dramatic. As a result, significant floods occurred at different places. One of them was observed near the town of Sveti Vlas, Nessebar Municipality, caused by the Drastela River (Figure 5). As a result, some holiday villas, hotels, and apartment buildings were flooded; a large part of the surrounding infrastructure was destroyed; cars and household items were swept away; social and human casualties were reported; and the water supply, sewage treatment, and electricity supply in the area were interrupted.

Figure 5. The flood wave on 3 October 2025.

The main reason for the flood can be attributed to the significant precipitation. There is no official weather station in the area, but the information from nearby measurements shows that for the plain area about 36 km south of the flooded zone, in the Chernitsite villa zone, over 250 L/sq.m. of rain fell in the previous 12 h on 3 October; in the Kraimorie district, also situated in that area, the amount of precipitation was 186 L/sq.m; in the area of the Ribarsko seliste, 117 L/sq.m; and in Izgrev village (in a forest zone), 410 L/sq.m [52]. The territory flooded by the Drastela River is mountainous, and similar precipitation also possibly occurred there.

The flood became a disaster, accompanied by widespread public response and local reports [52–54]. The significant damage caused is clearly identifiable. The flood waters carried large quantities of mud, inert materials, wood waste and broken branches, other vegetation, household items, cars, etc. (Figure 6a,b).

(**a**)

(**b**)

Figure 6. Flood impacts: (**a**) the situation in the built-up area days after the disaster; (**b**) some flood debris after the flood [54].

Bulgaria, as an EU member state, has adopted the current EU legislation [20–25]. As a result, the necessary flood protection measures are well implemented. Bulgaria has prepared FRMPs outlining flood risk areas [55–59]. Investigations are carried out according to a methodology specially developed and approved by the Ministry of Environment and Water of the Republic of Bulgaria (responsible for this activity) in line with the Flood Risk Directive [23] and the supporting documents. Developed Flood Risk and Flood Hazard maps cover areas that could be flooded under the following scenarios: low-probability floods—where the likely return period is greater than or equal to 1000 years, as well as under unpredictable events; medium-probability floods—where the likely return period is greater than or equal to 100 years; and high-probability floods—where the likely return period is greater than or equal to 20 years, where appropriate. The procedure covers flood extent for all return periods; flood depth (separate map) for each return period; hazard level versus flood depth (separate map) for each return period; flow velocities (separate map) for each return period; and flood depth and flood extent for climate change scenarios for the 100-year return period.

The areas affected by the flood of 3 October may be considered as flood-prone, but they do not fall within the mapped flood risk areas defined under the PURN [58] (Figure 7). Mapping was performed by specialized software and modeling: hydraulic modeling by Innovyse Infoworks ICM 2D, and GIS analysis and mapping by ArcGIS Desctop 10.7.

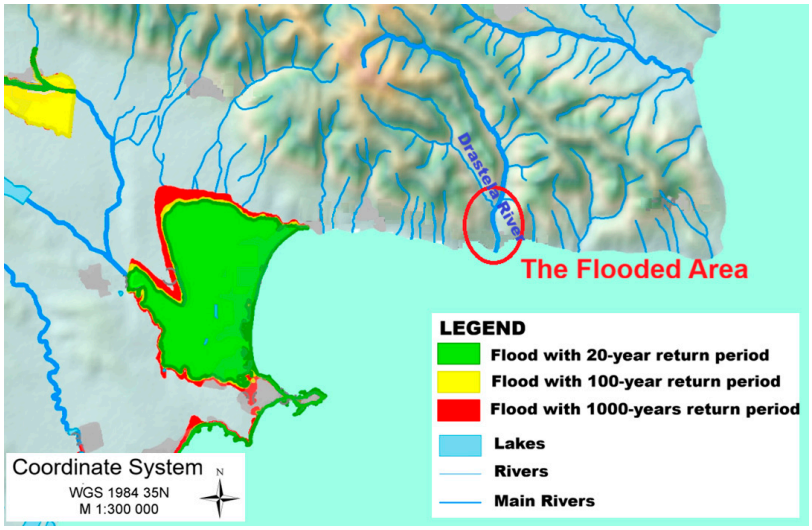
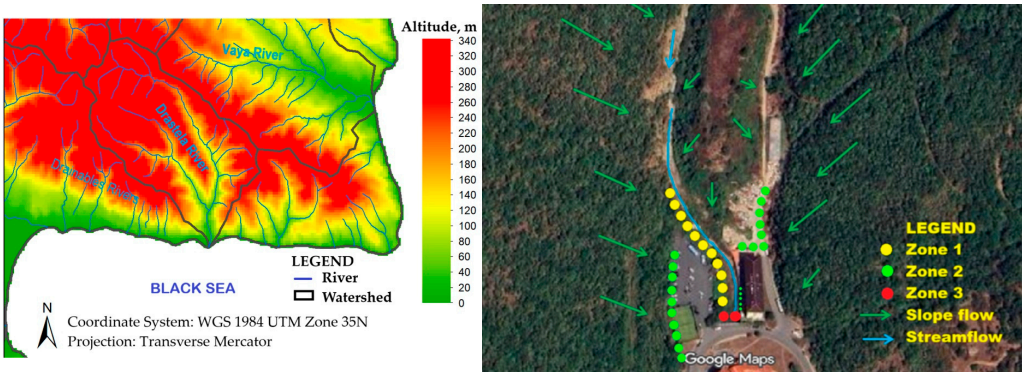


Figure 7. Areas under threat and risk of flooding, with additional delineation of the territory affected by the flood of 3 October 2025, based on the FRMP Black Sea Basin Management Directorate (2016–2021).

The Drastela River is a small Black Sea river, type R11 [59]. It tends to dry out, being dry or having minimum water for most of the year. In the past, no significant hydrometeorological phenomena had been observed there. There is also no information for flooding there. Its watershed is located on the southern slopes of the Stara Planina Mountains, at its confluence with the Black Sea, in the Burgas region. The territory is mountainous, with the gullies of the Drastela River reaching a built-up area. The anthropogenic development of the area began in 1985 with a few holiday villas and gradually expanded with new sites, hotels, and attractions. The transition from the mountainous to the built-up area passes through a small flat area, in which the ravine of the Drastela River, following the natural terrain forms, is located in a partially corrected riverbed—a one-side concrete river bank has been built in one section, with a length of about 80 m (Figure 8). To improve the area, the dried-up riverbed was later reclaimed with an underground section. Construction in the area continues to grow, with the development of new buildings and recreation and entertainment areas.

Figure 8. The riverbed after the mountain section, half a year after the flood.

When analyzing this situation, it was found that as a result of precipitation, two types of flow were formed in the watershed—slope flow and internal flow (in the urbanized area) (Figure 9).



(**a**) (**b**)

Figure 9. The Drastela River area: (**a**) the river watershed and (**b**) the transition area between the mountainous and the built-up areas. Based on Google maps, Copernikus, Maxar Technologies, Map Data 2026.

The flow passes two types of zones: one with natural debris (ND) and the other with a mixture of natural debris and anthropogenic waste (ND-AW). The first one carries debris of natural origin (mud, stone fragments, trees and broken branches, vegetation, etc.). The second one, flowing inside the built-up area, additionally carries waste with anthropogenic character (mud, stone fragments, gravel and sand, construction and attraction waste, trees and vegetation, household and garden tools, etc.). Details are presented in Table 1.

Table 1. Identified zones with flood debris.

Zone Type	Situation	Identified Damage and Waste
Zone ND	Non-anthropogenic impacted zone, before reaching the built-up area	Partial destruction of the riverbed; possible presence of an illegal dump; stone pieces, clay, gravel and sand, trees, broken branches, other vegetation, etc.
Zone ND-AW	The area before the river flow enters the underground passage	Partial destruction of the river bed; presence of mud, stone pieces, clay, gravel, sand, trees, broken branches, other vegetation, etc.; possible amount of destroyed concrete riverbed particles
Zone ND-AW	The place of entry of the river flow in the underground passage	Presence of mud, stone pieces, clay, gravel and sand, trees, broken branches, other vegetation, etc.; destroyed concrete riverbed particles
Zone ND-AW	The space between buildings	Significant amount of mud, stone pieces, clay, gravel and sand, trees, broken branches, other vegetation, and household and garden waste
Zone ND-AW	Destroyed attraction areas	Significant amount of mud, stone pieces, clay, gravel and sand, trees, broken branches, other vegetation, and other anthropogenic waste
Zone ND-AD	Roads and sidewalks	Significant amount of mud, stone pieces, clay, gravel and sand, trees, broken branches, other vegetation, and other anthropogenic and household waste

Looking at the flood process, the terrain configuration predisposes to the formation of some specific areas (Figure 9b). When debris from the mountain area is transported by a smaller flow, at low velocities, some of them may be deposited in Zone 1, potentially causing the riverbed to fill and the flow to be blocked. As the flow increases, some of it may overflow. As the flow and its energy increase in the event of a flood, the accumulated debris may be carried downstream. In this case, some of it may remain in Zone 2. Given

the local specifics, the area where the water of the stream passes underground is also extremely vulnerable (Zone 3). If debris accumulates there, the narrowed conductivity would also make downstream transfer difficult, making overflow very possible. When debris accumulates in any of the abovementioned zones, the formation of a strong flow (resulting from heavy rainfall) can cause the flow's high energy to breach the deposited material, and a flood wave with great destructive potential will form. The results will be extremely harmful. Based on the debris and anthropogenic waste present at the disaster site (Figure 10), it is highly likely that such a scenario unfolded.

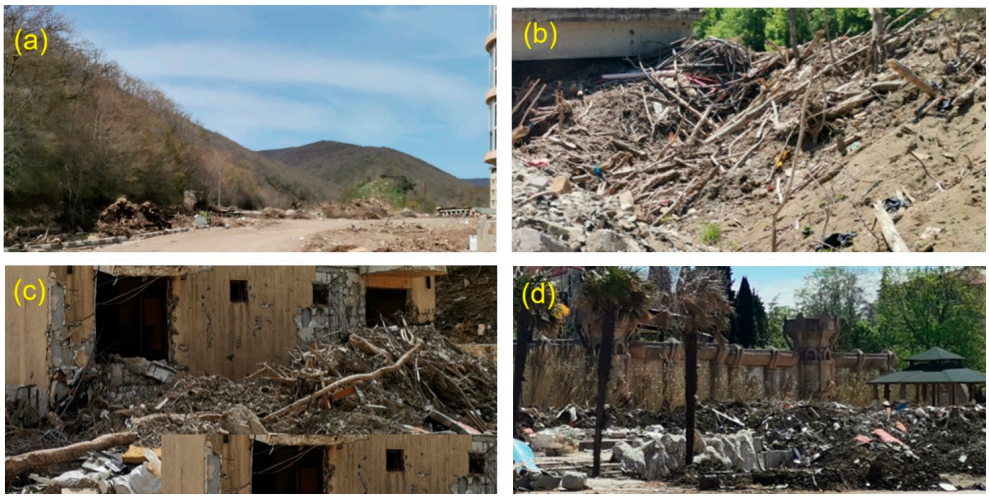


Figure 10. Flood debris and waste, over half a year after the disaster: (**a**) the flat part at the transition between the mountainous and built-up areas; (**b**) the place where the river flow enters the underground passage; (**c**) flood debris downstream; (**d**) destroyed attractions.

It should be noted that in the event of a flood, depending on the precipitation dynamics, the incoming waters may cause an alternation of the described processes. The formation of one or more flood waves is possible. The behavior of debris is not constant, it does not affect a certain place, and it has its own dynamics. In this specific case, the point where the flow enters underground can be characterized as a particularly sensitive element. If the flow capacity is restricted or the riverbed becomes filled with material there, the entire flow will be diverted into surface runoff. This runoff will merge with incoming water from the catchment area, forming a much larger flow. The volume of water diverted to surface flow was calculated using Formula (7) [32–34]. Data for various fill levels are presented in Table 2.

$$Q = \int_{\omega} dQ = \int_{\omega} u d\omega = v\omega, \tag{7}$$

where Q is the water discharge, ω is the cross-sectional area occupied by the flow, u is the flow velocity of the parcel, and v is the average flow velocity.

Table 2. Flow capacity at various riverbed fill levels.

№	Percentage of the River Cross-Section Filling with Debris	Q r.b., m^3/s	Q Overflow, m^3/s
1.	25%	64.80	21.40
2.	50%	43.20	43.20
3.	75%	21.40	64.80

The presented results outline the negative effect of filling in the riverbed. Calculations indicate that a significant volume of flow would pass through the existing area, which is

designed for holiday purposes, leisure, and recreation, and is not equipped to handle large masses of water. This explains the significant damage observed at the flood site.

5. Discussion

The recent development of extreme events over time shows that the climate and its factor-forming elements are changing. As a result, extreme hydro-climatic phenomena are becoming increasingly frequent [3,5–9]. This requires strengthening the capabilities for assessment, response, and mitigation of expected impacts, which can be achieved through the application and improvement of the current knowledge and methods used and the implementation of innovative tools, including risk assessments [59–64]. For practical needs, various methods and measures are being developed and improved, triggered by special legislation, aiming to guarantee the implementation of specific measures to deal with flood challenges. In the European Union, the issue is widely covered by water and environmental legislation, most notably by the Floods Directive [22] and its accompanying Flood Risk Management Plans (FRMPs) [23], which include maps that identify areas vulnerable to flooding. Maps are prepared using the latest hydraulic and geospatial methods and tools, taking into account recorded past events and the potential for future occurrences. However, dangerous floods have recently been observed even outside the designated areas. To find the reason for this, we turned to flood genesis, considering the role of debris and anthropogenic waste that are generated during flood events. They play a particularly destructive role by mixing with the water flow and transforming it into a rapidly moving slurry. Large debris and anthropogenic waste has a significant impact as they may cause blockages and damming of the current surroundings. When they move, if they come into contact with the neighboring environment, such pieces can lead to additional damage and the displacement or destruction of existing structures and features, such as riverbeds, levees, and infrastructure. All the destroyed material then enters the flow and increases the volume of flow debris and anthropogenic waste. Meanwhile, upon encountering an obstacle, all this material can come to a halt and accumulate, blocking the flow. In the event of a breach, the retained water in front of the accumulated debris and waste will trigger a destructive wave. The circumstances pointed out here initiated a review of the methods for assessing the behavior of flood flow, accounting for the presence of debris and waste within it.

Since the theoretical framework describes how the processes under study are approached, the comprehensiveness of the description of each element related to floods is significant. Any simplification of the process within the theoretical model inevitably leads to inaccuracies and deviations from the actual situation, yet it enables the element under consideration to be assessed based on current capabilities. The lack of familiarity with the theoretical basis can lead to certain misconceptions, causing underestimation of the simplified elements. However, by having a deep understanding of the capabilities of the methods and tools employed, one could make an informed decision regarding which approach to choose. In this article, the fundamental principles governing the theoretical description of fluid motion that underpin the methods and tools used in practice for flood assessment are considered. The methods and mathematical framework currently in use for flood description are presented, and it is demonstrated that the subject matter concerning debris and anthropogenic waste is insufficiently presented there. One of the reasons is that the accurate description of flood flow is incredibly complex work, as it involves chaotic physical interactions. Their characterization needs significant simplifications to be presented in a physically and mathematically acceptable manner. It is theoretically faced with a number of hydraulic limitations, but the observed theoretical basis confirms the possibility of mathematical expression and model implementation. A review of the

existing assessment approaches and developed commercial products shows that some of them have recently incorporated debris in traditional evaluation flood tools. The observed products were selected if they could be implemented at large scale and they were an option in the process of flood assessments, in line with the Floods Directive and related documents. They are products used both for hydraulic and spatial assessment purposes. Each of the considered products is connected to a certain flood process and debris behavior simplification, which may lead to inaccuracy and an underestimation of the results. There are various models incorporated into different assessment tools; however, none of them entirely cover the issues associated with flood flows containing debris or anthropogenic waste. The possibility for simultaneous analysis of moving heterogeneous debris and anthropogenic waste has not yet been clearly proposed. However, this does not diminish the impressive capabilities of the presented commercial products. The assessment of debris is a recent innovation. The weaknesses highlighted here aim to emphasize the relevance and severity of the problem. It is essential to emphasize the significance of the issue, as this could increase the interest in the topic and lead to a search for new, better solutions. Legislative support would accelerate this process.

This article presents a case study of a recent significant flood in Bulgaria. The procedures implemented in this flood were analyzed, demonstrating full compliance with legal requirements, including the availability of flood risk assessment maps. This raises the question of whether factors can be identified that were not previously assessed but played a significant role in the development of the flood. On-site observations indicate the presence of significant amount of debris, which correlated with local conditions and land coverage. Looking at the event site, the observed debris and waste can help in disaster chronology restoration and event reconstruction. Significant precipitation generates significant runoff and debris with a time-changing character—mud, dried trees and branches, leaves, new broken branches and trees, stones, etc. Moving downwards, reaching the flat territory on the border between the mountainous and flat built-up areas, they deposit partially in the riverbed. Two particularly vulnerable and dangerous sections can be identified in this territory in which accumulated debris significantly affects the riverbed by filling or blocking it and creating conditions for overflows. This leads to the conclusion that flood debris can contribute significantly to both the occurrence and severity of flood damage. In this regard, a more careful assessment of debris may be recommended.

6. Conclusions

Based on the presented information, it is clear that many investigations are carried out to better understand and describe flood behavior under real conditions. However, the existing theoretical basis does not precisely account for the formation and transport of debris and anthropogenic waste in the stream during a flood. This limitation is connected to the complex character of debris and anthropogenic waste themselves on one hand and to the absolutely specific flow movement and behavior in flood conditions on the other. This is related to the unpredictability of the formation and types of debris and anthropogenic waste. It also depends on many factors—the meteorological situation, the specific topography and slope patterns, land coverage, existing structures and their state, etc. This brief presentation outlined the challenges associated with this type of flow. Nevertheless, through considerable efforts and multidisciplinary collaboration, opportunities for improving assessment are being pursued. Traditional models are based solely on water depth and velocity, but modern capabilities allow for the inclusion of debris in realistic simulations. Using the most recent assessment tools, flood flow assessment results are achieved through significant simplification, which may lead to a certain degree of inaccuracy and underestimation. Nevertheless, a shift towards a more realistic approach to assessment

has already begun. Recent approaches introduce some additional factors and techniques alongside traditional flood evaluations. Future work could explore the subject matter in greater depth. Incorporating debris and anthropogenic waste as significant factors in flood assessment within the legal framework would greatly accelerate this type of development.

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Abbreviations

The following abbreviations are used in this manuscript:

FRMPs	Flood Risk Management Plans
EU	European Union
WFD	Water Framework Directive
RBMPs	River Basin Management Plans
PFRA	Preliminary Flood Risk Assessment
APSFR	Area of Potential Significant Flood Risk
SFHA	Special Flood Hazard Area
HEC-HMS	Hydrologic Engineering Center's Hydrologic Modeling System

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